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The VLT Interferometer and ESO Extrasolar Planet Search Projects

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Abstract. The coherent combination of light from a synthetic aperture array of several large diameter telescopes offers the possibility of attaining the ultimate achievable resolution and sensitivity from these devices. This combination promises to revolutionize the way we observe any astronomical source but especially the very faint or low S/N objects like the extrasolar planets that we might expect from recent theories and discoveries. The VLT Interferometer (VLTI) complex currently in an advanced state of construction on top of Cerro Paranal, Chile is being designed from the ground up to meet the stiff requirements associated with high precision measurements of these objects. We will review the present status and future prospects of this facility in terms of its ability to detect and characterize extrasolar planets.

1. Introduction

The Very Large Telescope is an interferometric complex offering four 8-meter telescopes (Unit Telescopes – UTs) and an array of 30 stations on which four 1.8-meter telescopes (Auxiliary Telescopes – ATs) can be relocated from night to night. The four UTs will be equipped with adaptive optics while the ATs will have fast tip-tilt correction for diffraction-limited spots in K-band. Up to 8 telescopes in dual-feed mode (feeding 2 stars each into the interferometer) could ultimately be combined together. Several instruments are foreseen or already installed, working in J-, H-, K- and N-band, with or without fringe stabilization. Phase-referenced imaging and high accuracy differential astrometry will also be implemented (Glindemann et al. 2000).

Basically, an interferometer produces fringes, i.e., modulation of the light intensity as a function of the Optical Path Difference (OPD) between the interferometric arms. The fringes are characterized by two parameters: their squared visibility (fringe contrast) and their phase (position of the fringe maximum). Information on the object can be extracted from these parameters.

The versatility of the VLTI, its sensitivity, its sky coverage and its built-in accuracy offer several possibilities to detect and characterize planets around other stars using both parameters. These possibilities are described here.

2. Squared Visibility (VINCI or AMBER)

A star with a planet can be considered as a binary object with a very high brightness ratio (10^4 to 10^9) and a very low separation (some milli-arcsec). The VLTI has the resolution capability to resolve systems like 51 Peg or τ Boo. However, the extreme brightness ratio poses a serious problem. Indeed, the squared visibility depends on the brightness ratio, on the planet position around the star and on the baseline. For a brightness ratio of one million, the modulation of the visibility as a function of the baseline is of the order of 10^{-6}.

VINCI, the current instrument devoted to K-band visibility measurements, is expected to have a visibility measurement accuracy of 0.1% with independent fringe tracking, on the ATs, in a 5 min exposure. AMBER, the J-, H-, K-band 3-way instrument to be installed in 2003, is claimed to go down to 0.01% accuracy. If observations can be synchronized with the period of the system observed by radial velocity techniques, Coude du Foresto (1999) has shown that a S/N ratio of 10 could be obtained on a system like τ Boo in a total observing time of 30 hours on the ATs, with VINCI, leading to its orbital parameters.

3. Differential Phase (AMBER & MIDI)

The apparent photocenter of an extrasolar system depends on the wavelength: at short wavelengths, it is closer to the star than at longer wavelengths (where the hot planet emits more light). The reverse is true between the continuum and a molecular absorbtion band (where the planet emits less light).

The displacement of the photocenter is translated in interferometry as a fringe phase, which depends on the wavelength. The astrophysical parameters of the system (angular separation on the sky, relative brightness, etc.) can be derived by fitting differential phase and differential visibility measurements obtained at various epochs. Lopez, Petrov & Vannier (1999) have shown that the differential phase can reach up to 10^{-3} radians between N- and K-band and some 10^{-4} radians between J- and K-band (51-Peg like star, at 10 pc, with a 1.4 $M_{Jupiter}$ black body at 0.1 AU). AMBER is expected to have a phase accuracy of some 10^{-6} radians in K-band and slightly higher in H- and J-bands. MIDI, the mid-infrared (10 μm) instrument to be installed in 2003, is expected to have an accuracy of 10^{-3} in N-band. Thus, differential phase can be detected by simultaneously interfering the light in several bands and measuring the differential position of the fringes.

Squared visibility and differential phase methods will bring the knowledge of *sin i* (orbit inclination to the plane of the sky) that cannot be obtained with radial velocities. They are especially sensitive to small or big planets close to their host star.

4. Astrometric Phase (PRIMA)

The tiny reflex motion of a star due to the presence of a planet can be detected astrometrically by measuring very accurately the position of the star photocenter with time. The reflex movement amounts to some tens or hundreds of micro-arcsec (μas), depending on the type of planet and star, and on the distance to the system. A Jupiter-like planet around a G-star at a distance 100 pc gives a signal of 50 μas; an Uranus-mass planet at 5 AU from a G-star, at 10 pc, a signal of 20 μas.

The Phase-Referenced Imaging and Micro-arcsec Astrometry (PRIMA) dual-feed facility, to be installed in 2005 (Delplancke et al. 2000), will allow performing differential narrow-angle astrometry with 10 μas resolution, limited by the atmospheric turbulence.

It can be shown that, in most of the cases implying Jupiter-mass planets or smaller ones, all stars having wobbles large enough to be measured by PRIMA should be bright enough to fringe track on them. Then, the astrometric references could be much fainter stars located in a narrow field (radius $\lesssim$ 30") around the target. The probability to find suitable faint astrometric references is relatively high (more than 50% up to 30° in galactic latitude) giving a good sky coverage.

Compared to radial velocities and to the previously described methods, astrometry is more sensitive to large planets far away from the star. It can be applied to any kind of star including pre-main sequence stars.

5. Imaging (PRIMA)

PRIMA will also allow phase-referenced imaging of the accretion nebula around the star. By using the same dual-feed principle, the object phase can be extracted. By observing the same object with many different baselines with PRIMA used in combination with AMBER or MIDI, one can reconstruct the object image, like in aperture synthesis radio interferometry. The resolution attainable with this method corresponds to a scale of 1 AU up to 1000 pc with AMBER and up to 100 pc with MIDI. It would allow to image the star forming regions and accretion disks and to detect the *cleaning effect* of a planet in them.

6. Nulling Interferometry (GENIE)

Interferometry can also be used as a kind of coronograph by adjusting the OPD to place a dark fringe on the star (Glindemann 2002). This method cancels the star light on a very narrow angle (some milli-arcsec) by a very high factor (10^{-3} to 10^{-4}), if atmospheric perturbations are compensated for. By tuning the interferometer to the planet separation, this one should pop-up in the image.

GENIE, the Ground-based European Nulling Interferometer Experiment for the VLTI, to be implemented after 2005, will be a testbed for DARWIN, the spatial nulling interferometer. This technique would also allow imaging the accretion disk and exo-zodiacal dust.

7. Gravitational Microlensing Events

Gravitational microlensing events, i.e., the sudden increase of a background star flux due to the lensing effect of a mass passing close to the line-of-sight, sometimes show secondary peaks that can be interpreted as the effect of a planet orbiting around the lens. However, the planet effect cannot always be distinguished from an artifact due to parallax effects. Moreover, the sole information about the star flux enhancement does not allow solving for the lens (and planet) mass. The VLTI can be used to disentangle this problem by either resolving and imaging the split image of the lensed star, or by detecting the tiny astrometric wobble of the image photocenter (Delplancke, Gorski & Richichi 2001).

The main limitations of the VLTI in this context are the magnitude ($K > 12$) and short duration (some hours) of such events. The probability for the VLTI to be in a configuration suitable for the observation at the moment of the event is not high. But, even if only 1 or 2 events can be observed per year, the additional information that interferometric observations could bring is worthwhile.

8. Conclusion

The VLT interferometer will soon offer many techniques to detect and characterize planets around other stars. They cover a large domain of planet characteristics (mass, orbital distance) and are complementary to each other. They also complement current planet detection methods (radial velocities, transits, microlensing) and would work best in collaboration with them. The different techniques will be progressively available: squared visibility measurements (VINCI, AMBER, microlensing) at end of 2003, differential phase (AMBER and MIDI) in 2004-2005, astrometry and imaging (PRIMA) in 2006, and nulling interferometry (GENIE) soon after.

The imaging at milli-arcsec resolution of the accretion disk from which any particular planet is born, simultaneously with the characterization of the planet mass and orbit, will add a new and exciting dimension to our understanding of both planetary and stellar formation mechanisms since the complex accretion disk is expected to be the cradle of these objects. The crucial exploration of the initial conditions for planetary formation in the stellar accretion disk as a function of age and composition will be finally possible.

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